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Coastal Stream Salinity and Its Impacts on Pemba Agriculture

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SIT Study Abroad

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Abstract

The extent of saltwater inundation of coastal streams was assessed on Pemba Island near agricultural areas in northeastern and northwestern regions of the island. Conductivity and pH were measured from water samples collected at various distances along the stream to determine the extent of salinity at different points in the tidal cycle. This salinity data, as well as the context of recent weather events, runoff, and geological characteristics of the region were used to determine the primary factors that influence changes in surface water salinity. The primary factor that influences surface water salinity was determined to be changes in stream discharge as a result of recent precipitation events or anthropogenic modifications. The impacts of these alterations are predicted to be amplified by climate change events such as sea level rise, storm surges, and changing precipitation patterns as well as increased anthropogenic usage. Implications of increased surface water salinity include lowered crop yield, abandoned farms, food and water scarcity, and negative economic impacts. Eastern Pemba was determined to be more affected by surface water salinization at present and will continue to be affected if serious mitigation strategies are not implemented.

Kiwango cha uingiaji wa maji ya bahari kupitia mito mbali mbali katika mwambao wa kisiwa cha Pemba ulifanyiwa uchunguzi karibu na mashamba ya kilimo yanayoonekana upande wa Kaskazini na Kusini mwa kisiwa cha Pemba. Viashiria vya umeme katika maji na hali ya tindi hali pamoja ukakasi vilifanyiwa vipimo kutoka kwenye sampuli za maji yalio kusanywa kutoka maeneo tofauti ya mito ili kuchunguza kiwango cha chumvi katika viwango tofauti kulingana na bamvua. Takwimu hizi za chumvi, pamoja na mabadiliko ya hali ya hewa ya hivi karibuni, mvua na hali tofauti ya giologia katika maeneo husika yaliweza kutumiwa ili kujua sababu za msingi zinazosababisha mabadiliko ya maji chumvi. Sababu za msingi zinazochangia ni kubadilika kwa mito kutowa maji kutokana na mvua za hivi karibuni au uchafuzi wa mazingira unaofanywa katika kubadilisha mifumo ya kimaumbile ya maji. Athari za mabadiliko haya yanachangiwa na mabadiliko ya hali ya tabia nchi ,kupanda kwa usawa wa maji bahari, upepo makali, na kubadilika kwa mzunguko wa mvua pamoja na kuongezeka kwa uchafuzi wa mazingira unaofanywa na wanadamu katika matumizi ya mali asili.Matokeo ya ongezeko la chumvi katika mito imesababisha kupungua mazao, kuachwa kwa mashamba yaliojaa maji chumvi, uchache wa chakula pamoja na maji, na pia athari mbaya za kiuchumi. Ukanda wa mashariki ya Pemba umeathiriwa zaidi maji chumvi kwa wakati huu na na athari hii itaendelea kwa hiyo kunahitajiwa kuchukuliwa hatua pamoja na kuweka mikakati inayotekelezeka.

Introduction

The impacts of climate change on coastal and island communities are increasingly visible through their effects on water and food availability. Developing coastal communities are especially vulnerable to these threats due to their reliance on natural resources for their livelihoods. Any changes to natural resource productivity on a seasonal or yearly basis can have devastating effects on food and/or income sources in these communities. Conservation of natural resources on islands is especially important due to their unique cultural and biogeophysical characteristics. Island communities rely on "long-term subsistence systems based on local resources and restricted land" (Kueffer & Kinney, 2017). This reliance on the natural world, coupled with the increasing threats of sea level rise, freshwater salinization, and other climate change impacts make coastal communities especially vulnerable to changes in their natural environment.

Saltwater intrusion occurs as a result of both natural and anthropogenic causes and has detrimental impacts on coastal human communities. Many coastal ecosystems have riparian areas that are useful for agriculture, and these water sources are highly impacted by increased salinity. Freshwater shortages are problematic for not only drinking water, but also to support agricultural practices linked to plant and animal productivity in coastal communities of East Africa.

The extent of salinity in coastal riparian systems may be a useful indicator in determining the extent of saltwater intrusion into agricultural fields near streams. These water quality issues are of interest to coastal farmers because increasing climate change factors, as well as local extraction of water, results in an increase in the salinization of freshwater. Salinity affects the ability for crops to uptake water and affects the rate of water infiltration from irrigation. The relative impact of saltwater intrusion on farm productivity in these upstream, coastal riparian areas will be evaluated by measuring the extent of this issue. With the impacts of sea level rise and future climate pressures on coastal stream salinity, this study will provide a baseline for future evaluations of the extent of freshwater salinization. The indications that these impacts have on food security and income for coastal communities is significant and mitigation strategies to deal with these issues would be beneficial in limiting these negative consequences.

This study aims to discover the extent of coastal stream salinization, evaluate the impacts of this intrusion in an agricultural setting, as well as propose possible mitigation strategies. The significance of this project is to evaluate how coastal agriculture may be impacted in areas where surface water salinity is increased and the implications of this issue in the context of climate change and regional trends. There is also a lack of geographical balance of scientific data about climate change, with marine and tropical environments especially underrepresented in literature (Reyes-Garcia et al., 2015). This study will provide valuable information about the extent of an important ecological issue in a region largely underrepresented in scientific research.

Background

Saltwater intrusion and surface water salinization both influence agricultural water quality requirements. On Pemba Island, the vulnerability to these factors is impacted by location and climate.

Saltwater Intrusion

Saltwater intrusion is the movement of saline water into freshwater sources. Although freshwater typically remains separate from seawater due to continuous seaward directional flow, seawater can intrude these freshwater sources under a variety of conditions. The susceptibility of coastal freshwater to saltwater intrusion is dependent on its proximity to seawater, intensive water demands, pumping, changes in land use, climatic variations and sea level fluctuations (Werner et al., 2012).

Changing climatic patterns, an increase of water consumption due to human communities, and the deterioration of current water infrastructure all contribute to saltwater intrusion in coastal regions (Yu & Packard, 2012). Climate change has both direct and indirect causes of increased saltwater intrusion. Direct causes include sea level rise, storm surges and changes in precipitation and evapotranspiration. Climate change indirectly increases the prevalence of saltwater intrusion through an increased need to pump groundwater in drier areas and reduced surface water discharge (Werner et al., 2012).

Although the Zanzibar Archipelago receives adequate rainfall to restore groundwater supplies, the islands' coralline nature and the increase in water consumption both contribute to an increase in water scarcity (Yu & Packard, 2012). These island communities are highly dependent on groundwater and its decreasing accessibility puts stress on people across the archipelago.

Sea level rise is an important factor which amplifies saltwater intrusion. Higher sea levels as a result of melting polar ice, expansion of water in warmer temperatures, and increased storm surges poses a threat to coastal freshwater sources. It is expected that within the period 2081 and 2100, sea levels will rise between 0.45 and 0.82 m (Mohammed & Scholz, 2018). In the Zanzibar Archipelago specifically, sea levels have risen at a rate of 0.28 cm/yr over the last 10 years (Kombo, 2019). These vulnerabilities will be enhanced by climate change, and salinity will become a much greater threat to coastal communities due to their reliance on fresh water.

According to Renaud et al (2014):

> In the absence of adaptation, salinity intrusion will slowly affect the freshwater and terrestrial ecosystems of exposed landscapes, contributing to a slow erosion of freshwater, agriculture-based livelihoods and of the availability of freshwater for domestic purposes, leading to increased poverty, health concerns, and potential displacement of populations (p. 82).

This emphasizes the importance of natural resource management and adaptation to climate change in coastal communities that rely heavily on these threatened ecosystems.

Tanzania is a member of the Intergovernmental Oceanographic Commission (IOC) and participates in the Global Sea Level Observing System (GLOSS) by measuring sea levels at sites in both Zanzibar and Dar es Salaam (Nhnyete & Mahongo, 2007). Data from 1984 to present and 1986 to present, respectively is available from these monitoring sites.

Surface Water Salinization in Estuaries

The dynamics of coastal stream salinity are controlled by tidal activity, the timing and volume of freshwater discharge, wind speed and direction, as well as density gradients caused by salinity (Kaplan & Munoz-Carpena, 2013). These factors also influence the frequency and duration of surface water salinity which exceeds critical ecological thresholds. Coastal estuaries are impacted by tidal forces which oppose stream flow. In estuaries, stratification often occurs when tidal currents and waves are not strong enough to mix the water column. The extent of mixing between fresh and saltwater in these estuaries is determined by the strength of these opposing forces.

Ion concentrations in streams are also impacted by the geological characteristics of the stream such as its source and channelization. Precipitation impacts stream salinity by introducing a greater volume of freshwater into the system, therefore changing tidal interactions, as well as increased runoff from nearby land areas.

Increased concentrations of dissolved salts with strong bases and carbonates as a result of human impacts cause increased pH values in freshwater systems. Agricultural use enhances freshwater salinization by the presence of bicarbonates and basic cations from fertilizers. Weathering is also enhanced by agriculture, which further adds to the generation of basic cations to cause alkalinity. Excess nutrients from wastewater or agricultural runoff also increase the pH of stream water due to increased primary production and therefore an increase in dissolved oxygen (Kaushal et al., 2017).

Measuring pH, specific conductivity, alkalinity, and base cations can indicate trends and changes in the salinity and alkalinity of freshwater streams over various scales of time and space. As climate change impacts weather patterns, natural processes, and the way humans interact with their environment, these measures will also change.

Water Quality in Agriculture

Agricultural output is influenced directly by the quality of soil and water used for crops. Common water quality problems faced in irrigation agriculture are salinity, water infiltration rate, and specific ion toxicity. Salinity reduces water availability to crops, especially in times of drought or excessive heat when the salts accumulate in higher concentrations in the root zone. The first water to be used by the plant is near the surface of the soil. As this water is used, salts are left behind, and eventually the remaining salts exist in a much higher concentration in the deep root zone of the plant. As a result, the concentration of salt in salinity impacted soils increases with soil depth. Symptoms of crops affected by salinity are similar to those of drought, including slow growth, wilting, bluish-green color, and/or waxier leaves. According to guidelines by the Food and Agriculture Organization of the United Nations (FAO), conductivity values between 700-3000 μS/cm are at a slight to moderate risk of impact on agriculture and values above 3000 μS/cm are at a severe risk (Ayers & Westcot, 1985).

Infiltration rate is also influenced by the presence of salt. The SAR (sodium absorption ratio) is a measure of the ratio of the number of sodium ions to the number of calcium and magnesium ions present in water. High salinity water increases infiltration of applied water, but a high SAR counteracts this by decreasing infiltration. These processes work at the same time and counteract each other to control infiltration rate of the irrigated water source (Ayers & Westcot, 1985).

Specific ion toxicity is a third water quality issue in agriculture. Ions such as sodium, chloride, and boron can accumulate in crops and damage them. The crops most vulnerable to this kind of toxicity are perennial tree crops, such as citrus. Warmer climates cause higher accumulation of these ions and therefore crops in the tropics and subtropics are at a higher risk. Symptoms of specific ion toxicity in crops are marginal leaf burn and interveinal chlorosis (Ayers & Westcot, 1985).

Study Site

Pemba Island is located in the Zanzibar Archipelago, East Africa, 50 km from mainland Tanzania. Pemba (Figure 1) is a coralline island with hilly topography, ragged limestone, and well-draining soil. Its topography, as well as altered weather patterns in the area during the last decade, make Pemba prone to drought and therefore a challenging location for agriculture. In western Pemba, hilly topography also amplifies runoff from agricultural fields which causes further damage to surface water sources through eutrophication. Eastern Pemba, however, is much flatter and also much more exposed to winds and other influences of the deep sea of the

Indian Ocean. This makes eastern Pemba especially prone to storm surges and any impacts that persist due to flat topography and a lack of seawater drainage. Despite these challenges to agriculture, the island relies heavily on its agriculture to sustain its population of 400,000.

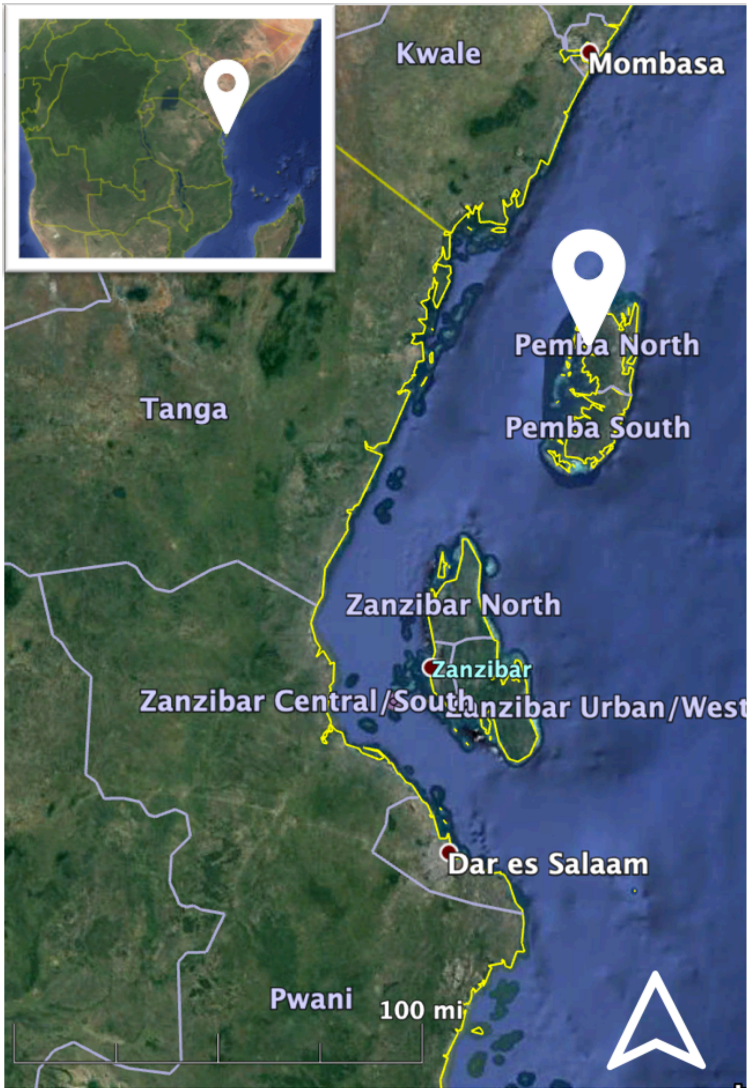

Figure 1: Ariel view of the Zanzibar Archipelago (Unguja and Pemba) from Google Earth. Pemba Island, 50 km from mainland Tanzania, is the study site for this project. Retrieved December 5, 2019.

Five streams were selected in northwestern and northeastern Pemba (Figure 2): three near the town of Wete in western Pemba and two in eastern Pemba. These five streams were selected due to their differences in location, length, flow, and profile shape. All of these streams are near farms that have a history of seawater intrusion or are near farms that have been abandoned due to the negative effects of seawater intrusion.

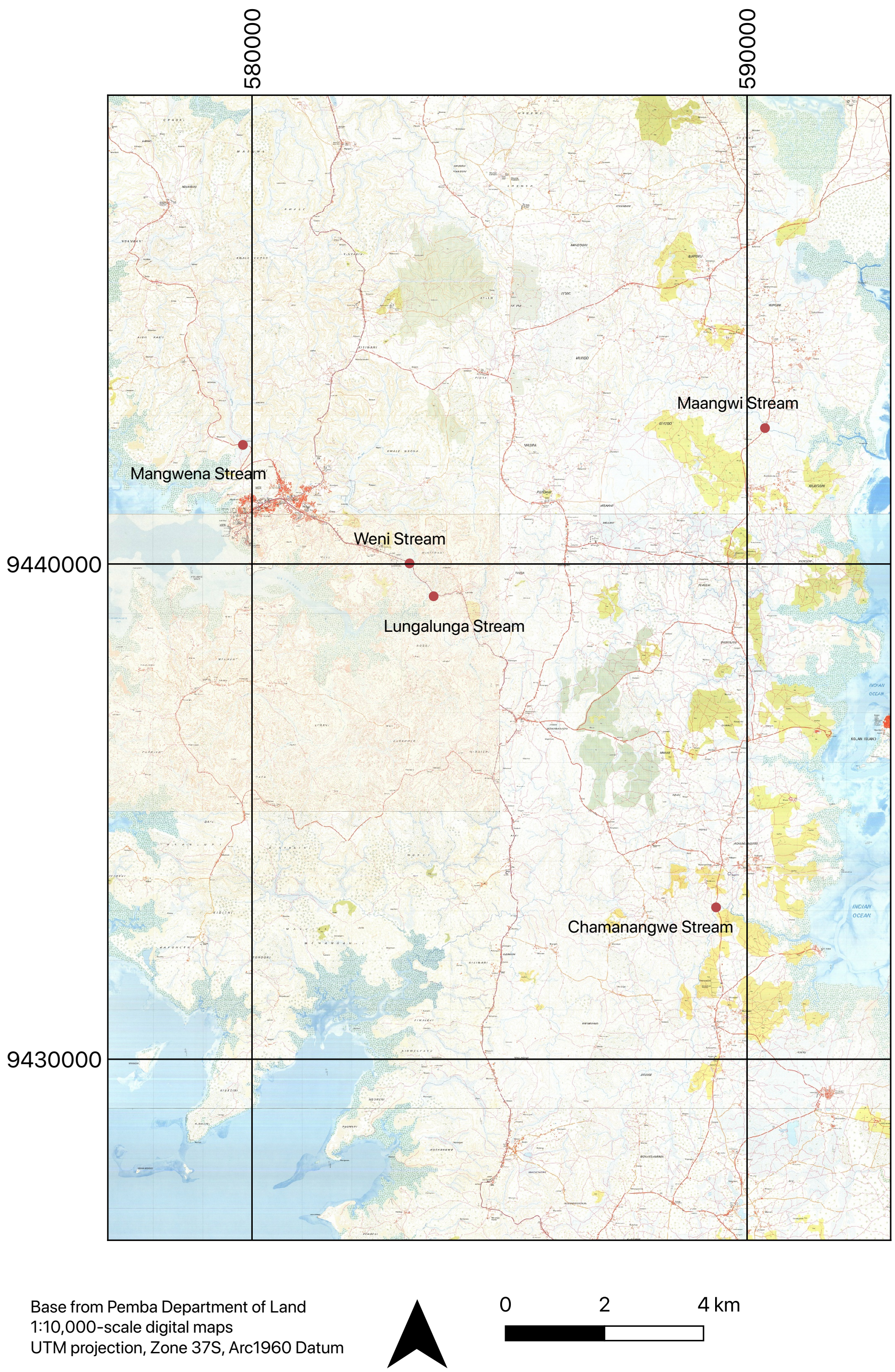

Figure 2: Map of study stream locations. This map shows the five streams evaluated in this study in Central Pemba. Three streams were chosen in western Pemba and two were chosen in eastern Pemba.

There are significant geological differences between the western side of the island and the eastern side. The western side has deeper topsoil, which makes it more suitable for cultivation. The soils are mostly clays and loams, high in iron, and are acidic. Agriculturalists on the western side of the island are limited by nutrients such as potassium and calcium, which are essential to crops such as pumpkins and tomatoes. The eastern side of the island is a flatter coral rag forest with very little topsoil, but fewer challenges of runoff than the hillier western side. Nitrogen is the major limiting nutrient for agriculture in eastern Pemba. Saltwater intrusion has impacted eastern Pemba to a greater extent due to its exposure to the Western Indian Ocean as well as its flat topography. This has resulted in many more abandoned agricultural areas in eastern Pemba than in the west.

Stream 1: Mangwena

Mangwena Stream is a channelized stream in NW Wete near a large agricultural valley that primarily grows rice and cassava. The source of the stream is a spring and the stream is also dammed upstream of the sample site. Mangrove crabs are present along the stream banks all the way from the mangroves to the bridge, which indicates the presence of salt. The stream intersects the road 350 m from the mangroves. Although the land directly around this stream is flat, there are large hills on all sides of the stream valley.

Streams 2 and 3: Weni and Lungalunga

Weni Stream and Lungalunga Stream are two channelized streams east of Wete in Limbani, eastern Pemba. Both streams originate from springs and are surrounded by a large agricultural area of cassava, banana, mango, and a variety of vegetables but also many hills covered with natural vegetation. There are rice farms upstream of the sample sites on both streams and Weni is dammed upstream of the sample site. Weni also has a borehole out of a spring that would typically feed into the stream. These streams merge 110 m from the mangroves. Weni intersects the road at 1210 m from the mangroves and Lungalunga intersects the road at 330 m from the mangroves.

Stream 4: Maangwi

Maangwi Stream is in eastern Pemba near the village of Kiungoni. This stream originates from a spring and intersects the road 1200 m from the start of the mangroves. This region is very flat, and the stream is braided through large rice farms between the mangroves and bridge. At the beginning of the rice farms, there is a manmade ridge built to prevent seawater from intruding into the farms. There are also efforts by the community to plant mangrove saplings near the rice farms as a mitigation strategy against seawater intrusion.

Stream 5: Chamanangwe

Chamanangwe Stream is a highly channelized stream in eastern Pemba near a large agricultural area of primarily cassava, vegetables, and tree crops such as coconut, banana, and mango. The stream originates from a spring. This region is hillier than Maangwi, but flatter and more dominated by agriculture than western Pemba. Near the stream, there are many areas that have been abandoned as farmland due to saltwater intrusion. Large rice farms not immediately next to Chamanangwe, but in the same region have been abandoned due to seawater intrusion and many others are struggling to mitigate the impacts of saltwater.

Methods

This study was conducted on three streams near Wete, Pemba: Weni, Lungalunga, and Mangwena and two streams in Eastern Pemba: Maangwi and Chamanangwe. These streams were selected with the help of a local government official who is familiar with the impacts of saltwater intrusion on local farms. All of these streams were selected due to their close proximity to agriculture and the coast as well as a history of problems of saltwater intrusion. Water samples were collected from each stream starting at the edge of the coastal mangrove forest and at various intervals upstream until the intersection between the stream and a nearby road. Figure 3 shows the sample sites used at each stream. At these bridge intersections, observations of water flow showed that it was sufficient in preventing movement of saltwater further upstream. The coordinates of each sample site were recorded using a Garmin GPS and QGIS was later employed to measure the distance of each sample site to the ocean. Water was collected from study sites at both low and high tide, within an hour before or after the peak tide time on that day.

For each stream, dominant land use near the stream was determined through observations and recorded, as well as stream channelization and stream sediment load. Current and recent weather conditions as well as any notable changes in runoff or stream discharge were also recorded in the field. Vegetation around each site was also observed for visual clues of negative impacts due to salinity. Water samples were analyzed for conductivity and pH.

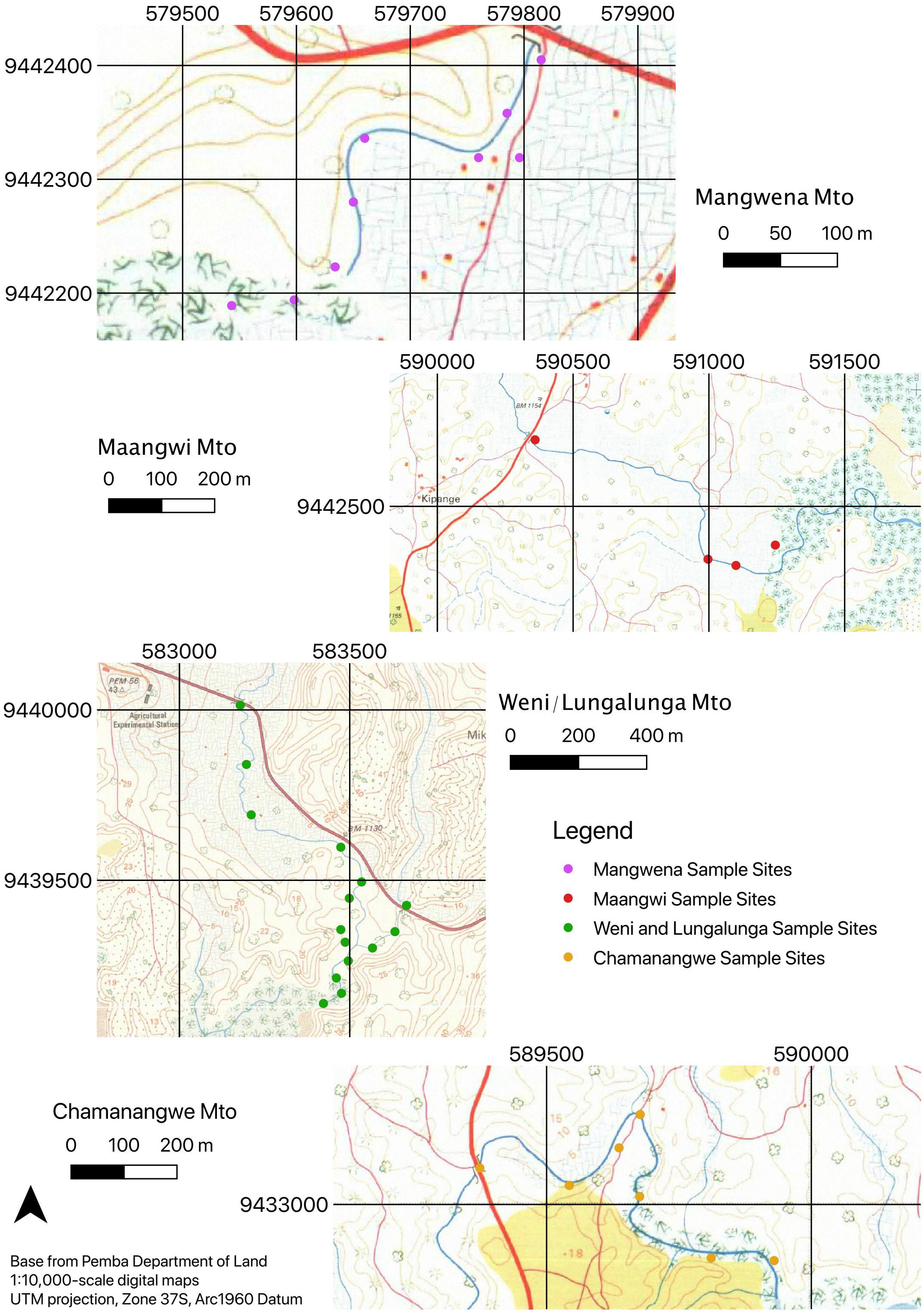

Figure 3: Sample site locations at each stream. Water samples were collected from each stream at the sample sites marked in these maps using a Garmin GPS.

Results

Conductivity and pH were measured on water samples taken from various intervals along each stream. Conductivity values between 700-3000 μS/cm are at a slight to moderate risk of impact on agriculture and values above 3000 μS/cm are at a severe risk (Ayers & Westcot, 1985). Summary data for stream characteristics and risk level was evaluated at various distances for each of the five streams (Table 1).

Table 1: Summary of Salinity in Study Streams. The risk of salinization on each stream is evaluated at three distances along each stream, as well as channelization, dominant land use, and any observations related to salinity near the study site. Risk categories are none (N), slight to moderate (M), and severe (S), adopted from Ayers & Westcot (1985).

	Stream 1 Mangwena	**Stream 2 Weni**	**Stream 3 Lungalunga**	**Stream 4 Chamanangwe**	**Stream 5 Maangwi**
East or West	West	West	West	East	East
Land Use	Agriculture (rice and cassava)	Agriculture (rice, cassava, vegetables)	Agriculture (rice, cassava, vegetables)	Agriculture (tree crops, cassava)	Agriculture (rice)
Observations related to salinization	Negative velocity and increased water depth at high tide, mangrove crabs along stream bank, dam upstream of sample site	Local farmer accounts of saltwater 800 m upstream, dam and borehole upstream of sample site	No dam upstream of sample site	Abandoned farms as far as 670 m upstream, flooding at high tide	Many mitigation strategies implemented
Channelized (1) Braided(5)	1	1	2	1	5
Risk at 0 m	N	M	M	S	N
Risk at 100 m	N	M	N	S	N
Risk at 300 m	N	N	N	S	N
Risk at Bridge Intersection	N	N	N	N	N

Stream 1: Mangwena

Mangwena was studied on three different days during the study period, each with different weather patterns. Mangwena is a highly channelized stream in NW Wete in close proximity to many rice and cassava farms. It was common to see runoff from these nearby farms into the stream. Mangrove crabs were observed along the stream's banks from the mangroves all the way up to the bridge. The average pH for Mangwena Stream was 7.9.

On November 13th, the morning low tide was followed by heavy rain throughout the day resulting in a greater sediment load and amount of runoff at the afternoon high tide. There were significantly lower conductivity values after the heavy rainfall compared to before (Figure 4).

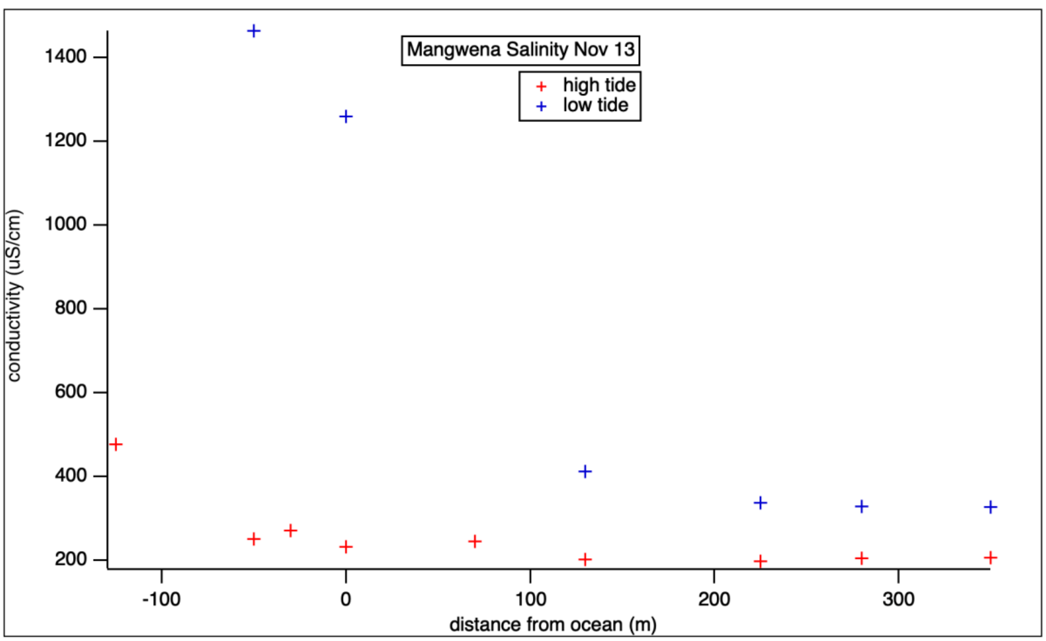

Figure 4: Mangwena Salinity Nov 13. Conductivity values on Mangwena Stream were obtained from water samples collected at intervals from the mangroves to the bridge at the intersection of the stream and the road. Heavy rainfall occurred between low tide and high tide.

On November 15th, there was a short rain in the morning before low tide and although there was very little runoff observed, there was a lot of water present from heavy rain in the previous days. There was no rain between the morning low tide and evening high tide.

There was not much difference in conductivity values between tidal cycles (Figure 5).

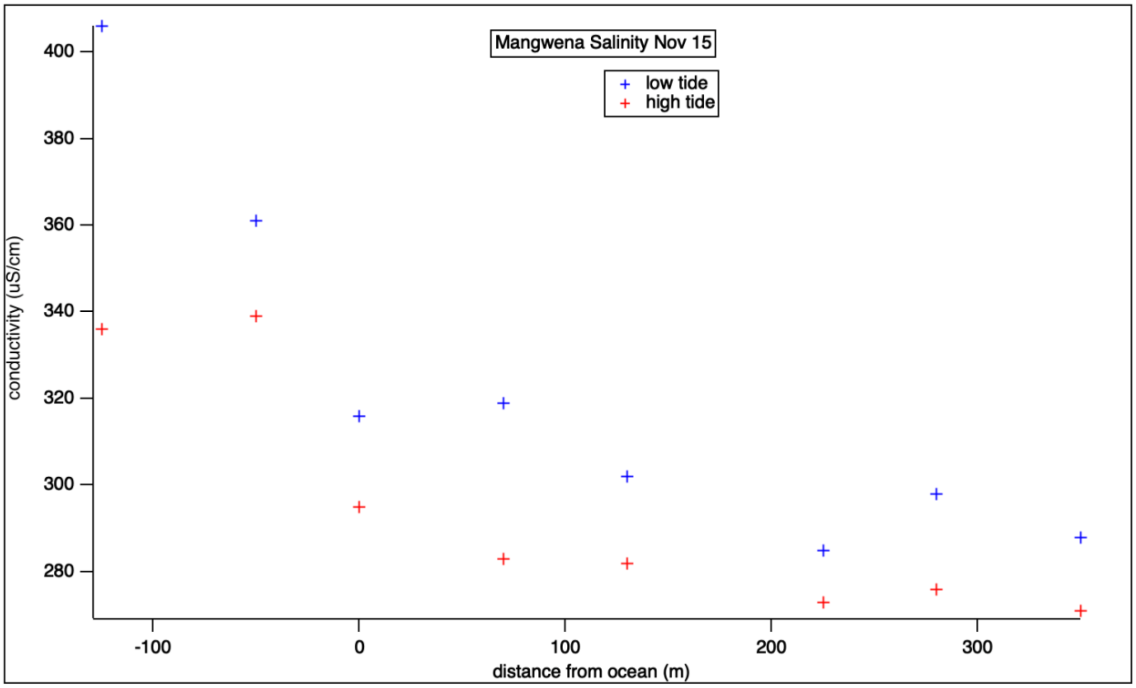

Figure 5: Mangwena Salinity Nov 15th. Conductivity values on Mangwena Stream were obtained from water samples collected at intervals from the mangroves to the bridge at the intersection of the stream and the road. The days before this data set had moderate rainfall.

On November 18th, there had been no significant rainfall in the days prior. High tide salinity values are significantly higher in the mangroves and similar to the low tide values once out of the mangroves (Figure 6).

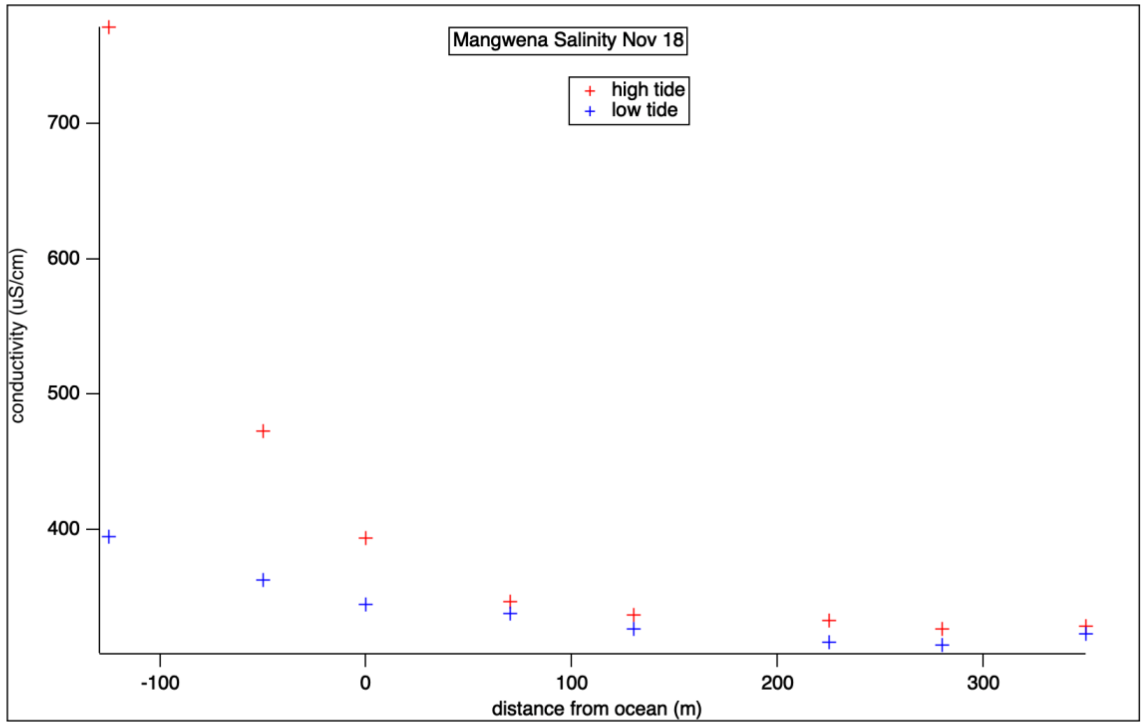

Figure 6: Mangwena Salinity Nov 18. Conductivity values on Mangwena Stream were obtained from water samples collected at intervals from the mangroves to the bridge at the intersection of the stream and the road. There was no recent rainfall in the days before this data set.

Conductivity values at Mangwena are compared based on the differing weather events on the three study days. November 13th had heavy rain, November 15th had a short rain, and November 18th had no rain. Conductivity values are higher throughout the stream on days with less rainfall, but all conductivity values are well below the 3000 μS/cm mark for suitable agricultural use (Figure 7).

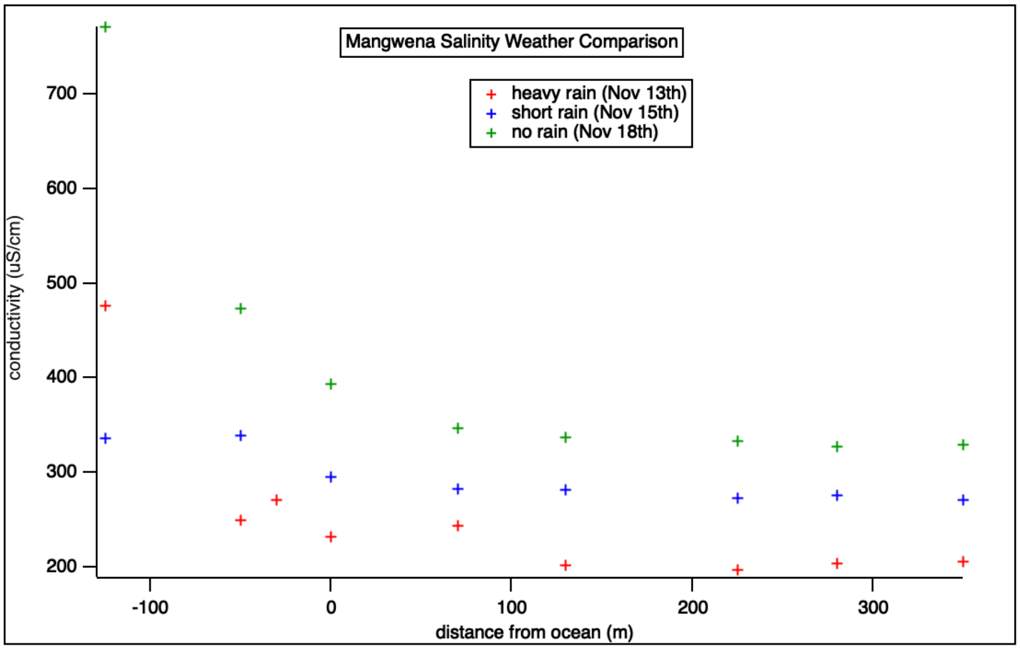

Figure 7: Mangwena Salinity Weather Comparison. Conductivity values on Mangwena Stream were obtained from water samples collected at high tide at different distances from the ocean and on days with different weather patterns.

Stream 2: Weni

Weni Stream was studied on three different days during the study period. Weni is a highly channelized stream east of Wete in Limbani that intersects with Lungalunga 110 m from the mangroves. The topography around Weni is hilly, and the hills are covered with natural vegetation with a lot of farmland in the surrounding valleys and flat land between hills. The average pH for Weni and Lungalunga was 7.65.

On November 14th, samples were taken along the stream from the mangroves to the bridge intersecting the nearby road. There was heavy rain the previous day and a lot of visible runoff into the stream. Conductivity values were very high during high tide in the mangroves but were close to the low tide values just outside of the mangroves (Figure 8).

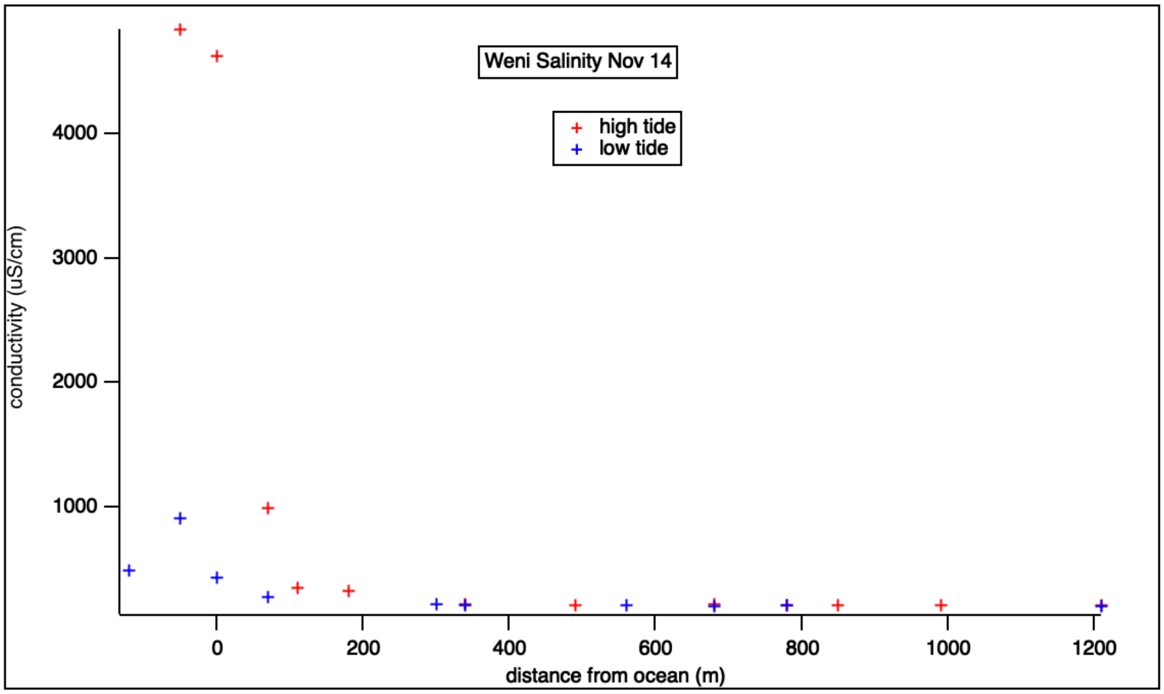

Figure 8: Weni Salinity Nov 14. Conductivity values on Weni Stream were obtained from water samples collected at intervals from the mangroves to the bridge at the intersection of the stream and the road.

On November 19th, the morning high tide was followed by heavy rainfall before the afternoon low tide. The sample area was quite dry in the morning, as there had been no significant rainfall in the previous days, but after the midday rain, there was more water present around the sample area and the stream was moving much faster and appeared to be clearer. High tide conductivity values were significantly higher than low tide values up to 100 m from the start of the mangroves (Figure 9).

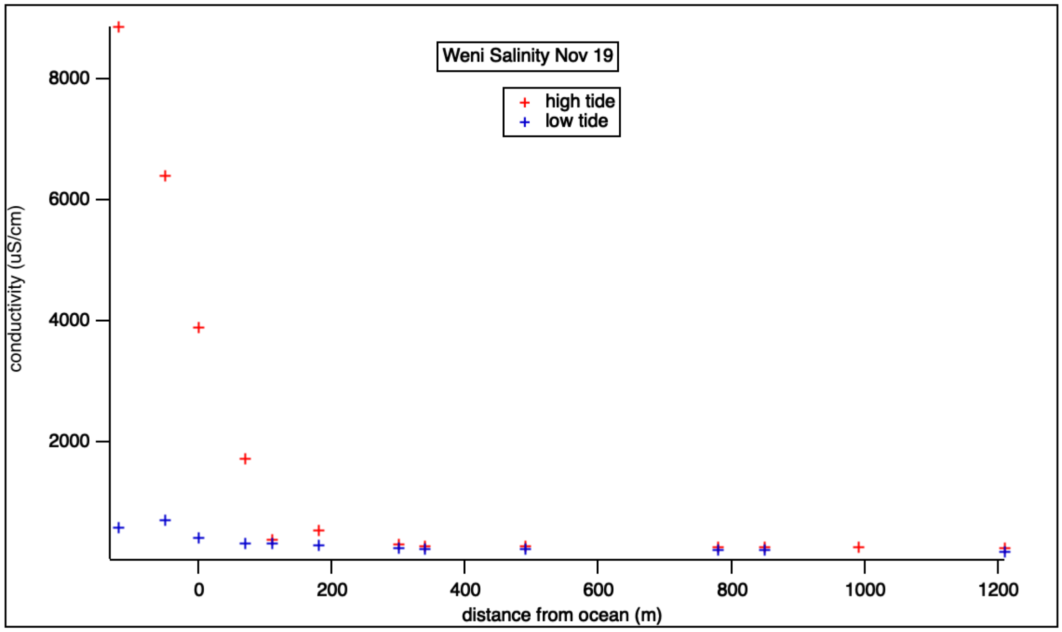

Figure 9: Weni Salinity Nov 19. Conductivity values on Weni Stream were obtained from water samples collected at intervals from the mangroves to the bridge at the intersection of the stream and the road.

On November 24th, Weni samples were collected from the mangroves to the intersection with the nearby road. There had been a lot of rainfall in the previous days and the morning low tide was followed by a heavy midday thunderstorm before high tide. At the afternoon high tide, there was heavy runoff from the surrounding land and a lot more water present throughout the study area compared to the morning low tide. Conductivity values were low compared to other days at Weni for both low and high tide samples, even in the mangroves (Figure 10).

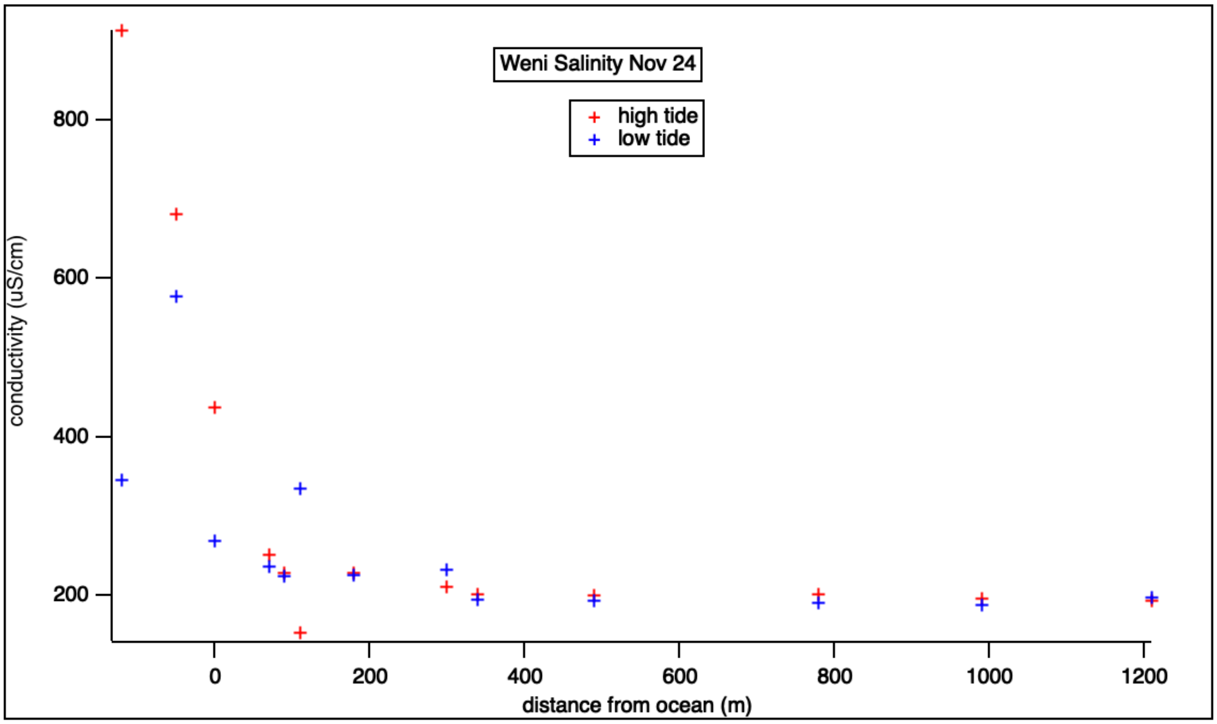

Figure 10: Weni Salinity Nov 24. Conductivity values on Weni Stream were obtained from water samples collected at intervals from the mangroves to the bridge at the intersection of the stream and the road.

Stream 3: Lungalunga

Lungalunga Stream was studied on three different days during the study period. Lungalunga is a semi channelized stream east of Wete in Limbani that intersects with Weni 110 m from the mangroves. The topography around Lungalunga is hilly, and the hills are covered with natural vegetation. There is some farmland around the sample area, but more farmland along Lungalunga is upstream of the sample area.

On November 14th, samples were taken along the stream from the mangroves to the bridge intersecting the nearby road. There was heavy rain the previous day and a lot of visible runoff into the stream. Conductivity values were very high during high tide in the mangroves but approached the low tide values 100 m from the mangroves (Figure 11).

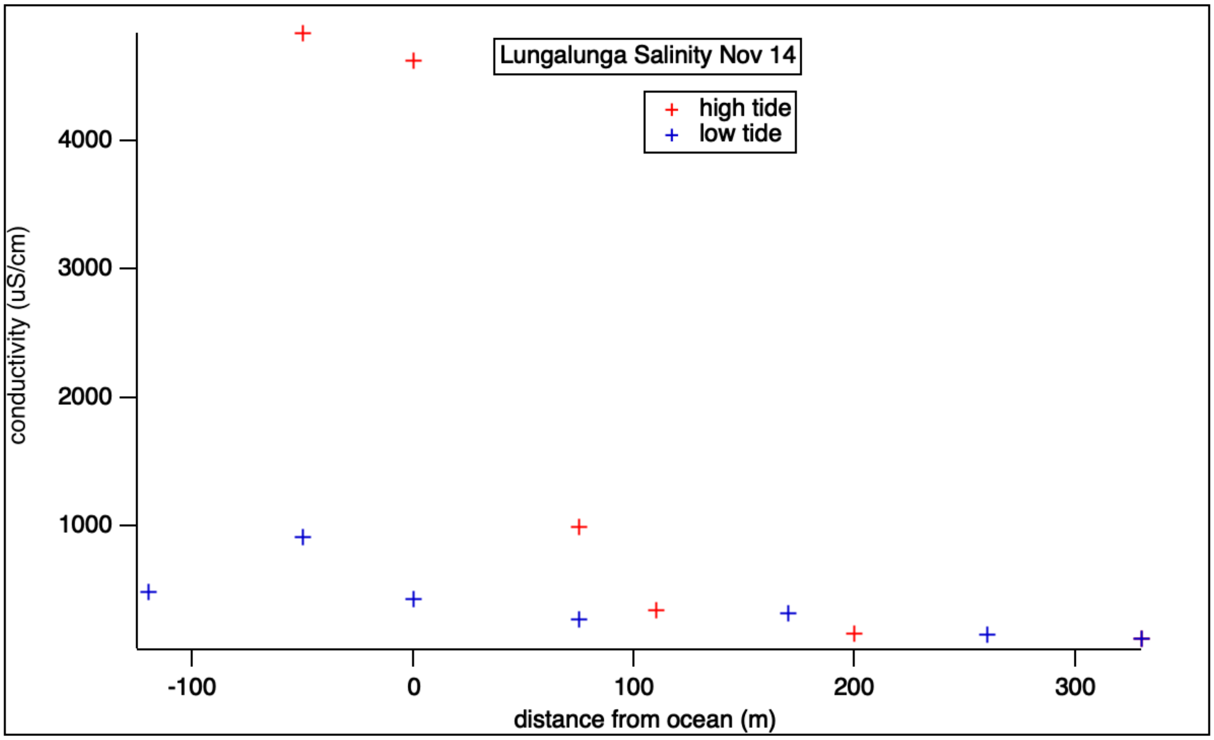

Figure 11: Lungalunga Salinity Nov 14. Conductivity values on Lungalunga Stream were obtained from water samples collected at intervals from the mangroves to the bridge at the intersection of the stream and the road.

On November 19th, the morning high tide was followed by heavy rainfall before the afternoon low tide. The sample area was quite dry in the morning, as there had been no significant rainfall in the previous days, but after the midday rain, there was more water present around the sample area and the stream was moving much faster and appeared to be clearer. High tide conductivity values were significantly higher than low tide values up to 100 m from the start of the mangroves (Figure 12).

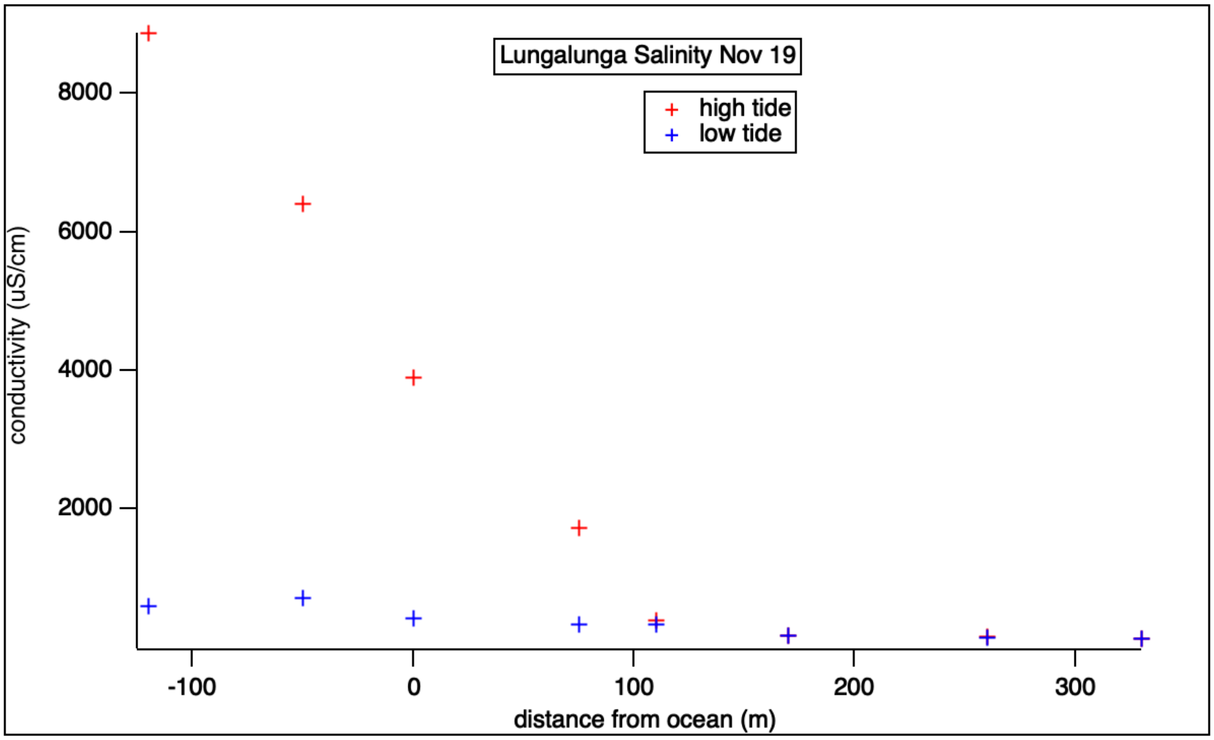

Figure 12: Lungalunga Salinity Nov 19. Conductivity values on Lungalunga Stream were obtained from water samples collected at intervals from the mangroves to the bridge at the intersection of the stream and the road.

On November 24th, samples were collected from the mangroves to the intersection with the nearby road. There had been a lot of rainfall in the previous days and the morning low tide was followed by a heavy midday thunderstorm before high tide. At the afternoon high tide, there was heavy runoff from the surrounding land and a lot more water present throughout the study area compared to the morning low tide. Conductivity values were extremely low compared to other days at this location for both low and high tide samples, even in the mangroves (Figure 13).

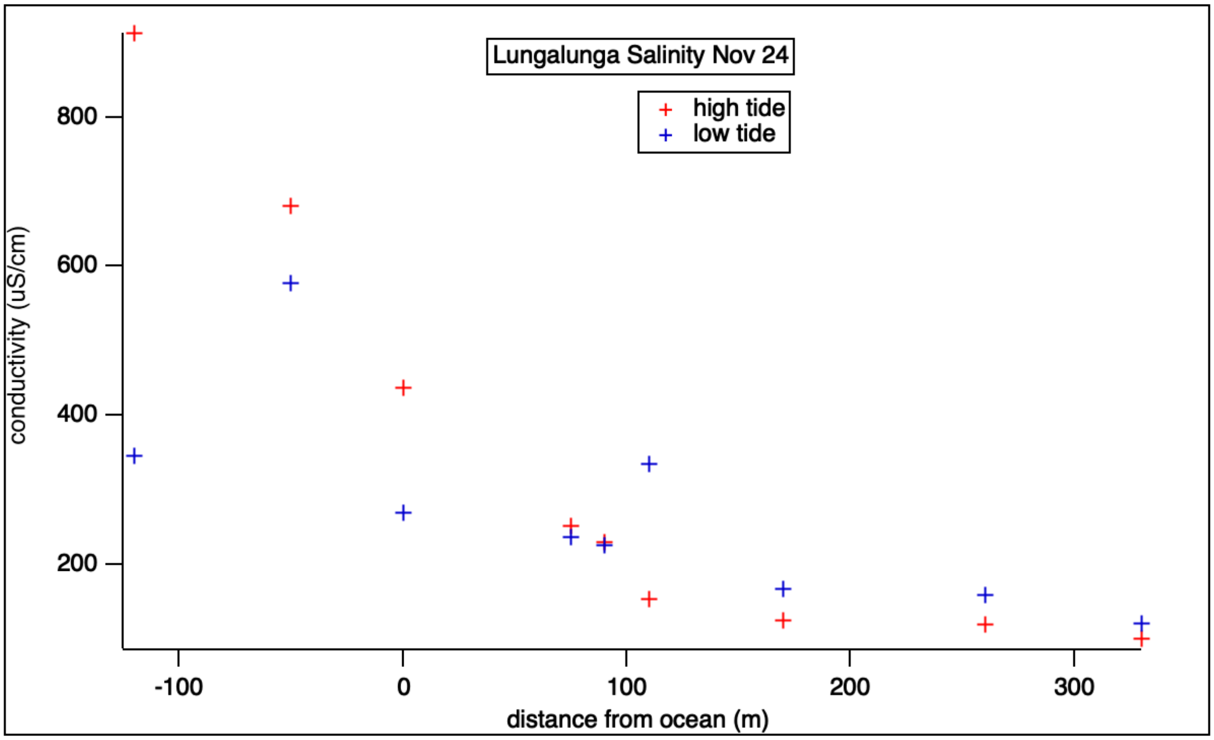

Figure 13: Lungalunga Salinity Nov 24. Conductivity values on Lungalunga Stream were obtained from water samples collected at intervals from the mangroves to the bridge at the intersection of the stream and the road.

Stream 4: Chamanangwe

Chamanangwe Stream is a highly channelized stream in eastern Pemba with flat topography and many different types of farms. This site was studied on two different days during the study period, once at high tide on November 11th and at both low and high tide on November 25th. Both days were dry, but the 25th had more recent rainfall than the 11th. On November 11th, samples were taken 50 m, 400 m, 670 m, and 1000 m from the mangroves and the conductivity values were 10490 µS/cm, 2350 µS/cm, 808 µS/cm, and 635 µS/cm, respectively. Similar data was obtained on the 25th, showing significantly higher conductivity values at high tide as far as 600 m from the mangroves (Figure 14). The average pH of Chamanangwe Stream was 8.09.

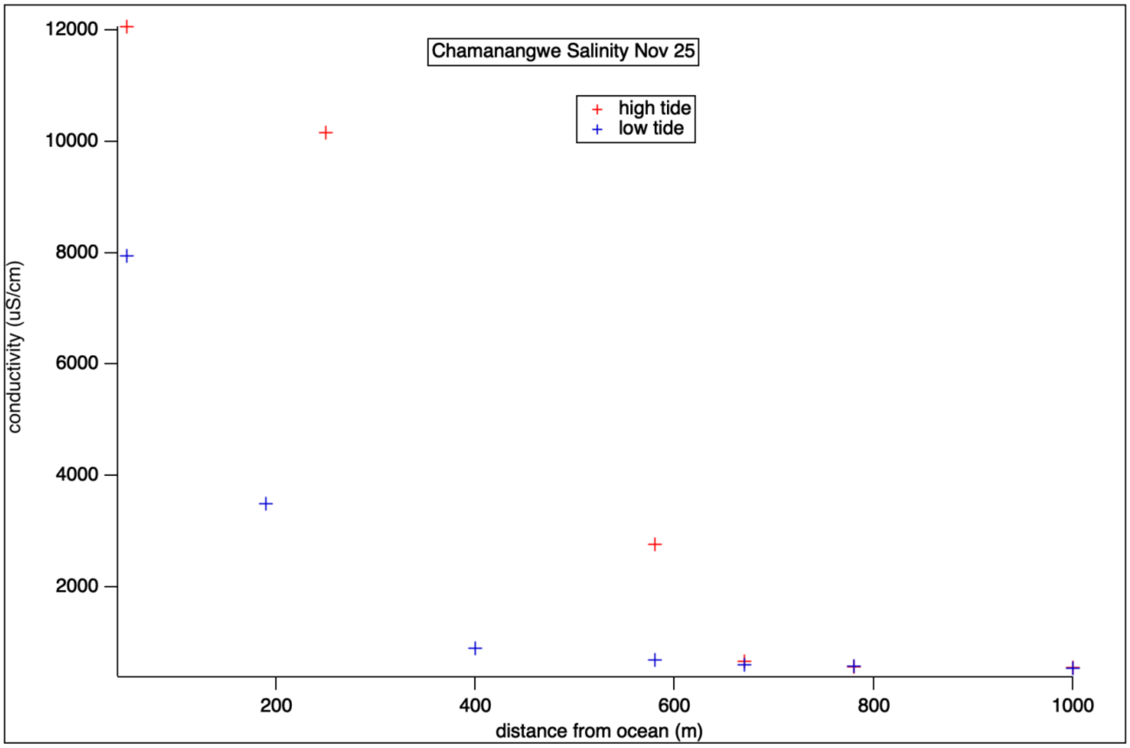

Figure 14: Chamanangwe Salinity Nov 25. Conductivity values on Chamanangwe Stream were obtained from water samples collected at intervals from the mangroves to the bridge at the intersection of the stream and the road.

Abandoned cassava and rice farms were visible near the stream from 50-670 m from the start of the mangroves (Figure 15). The surrounding land was clearly impacted by saltwater intrusion due to many patches of bare soil and flooding in this area during high tide.

Figure 15: Abandoned cassava field. Located near Chamanangwe Stream, approximately 670 m from the start of the mangroves, there were visible signs of seawater intrusion such as this recently abandoned cassava field. During high tide, parts of this area were flooded.

Stream 5: Maangwi

Maangwi Stream is a braided stream in eastern Pemba near the village of Kiungoni. This stream is braided into many small sections through the rice farms in a flat valley. On the edge of the rice farms, before the mangroves, there is a manmade ridge built to prevent saltwater intrusion (Figure 16). Mangrove crab holes were observed on the ridge and in the image the outlet of Maangwi to the mangroves is visible, as well as the flooded rice fields. The average pH of Maangwi Stream was 8.1.

Figure 16: Maangwi intrusion ridge. A manmade ridge was built between the Maangwi rice farms (left) and mangroves (right) to prevent seawater intrusion.

At Maangwi, there was also an area that had been planted with mangrove saplings as a mitigation technique against saltwater intrusion. These saplings were planted just beyond Maangwi on the right in Figure 16. The mangrove saplings (Figure 17) are primarily red mangrove (*Rhizophora mucronata*) and white mangrove (*Ceriops tagal*) species.

Figure 17: Mangrove saplings to mitigate saltwater intrusion. Near the rice farms and Maangwi Stream, there was an area of young mangrove saplings that had been recently planted.

Maangwi Stream was studied on two different days during the sample period. On November 11th, samples were taken at high tide at the outlet of Maangwi to the mangroves in Figure 15 and at the bridge intersecting the road. The conductivity measures were 464 μS/cm and 275 μS/cm, respectively. On November 25th, samples were taken at two additional locations between the outlet and the bridge which showed significantly higher values at high tide than low tide (Figure 18). There was no significant rainfall on either of the two days at Maangwi.

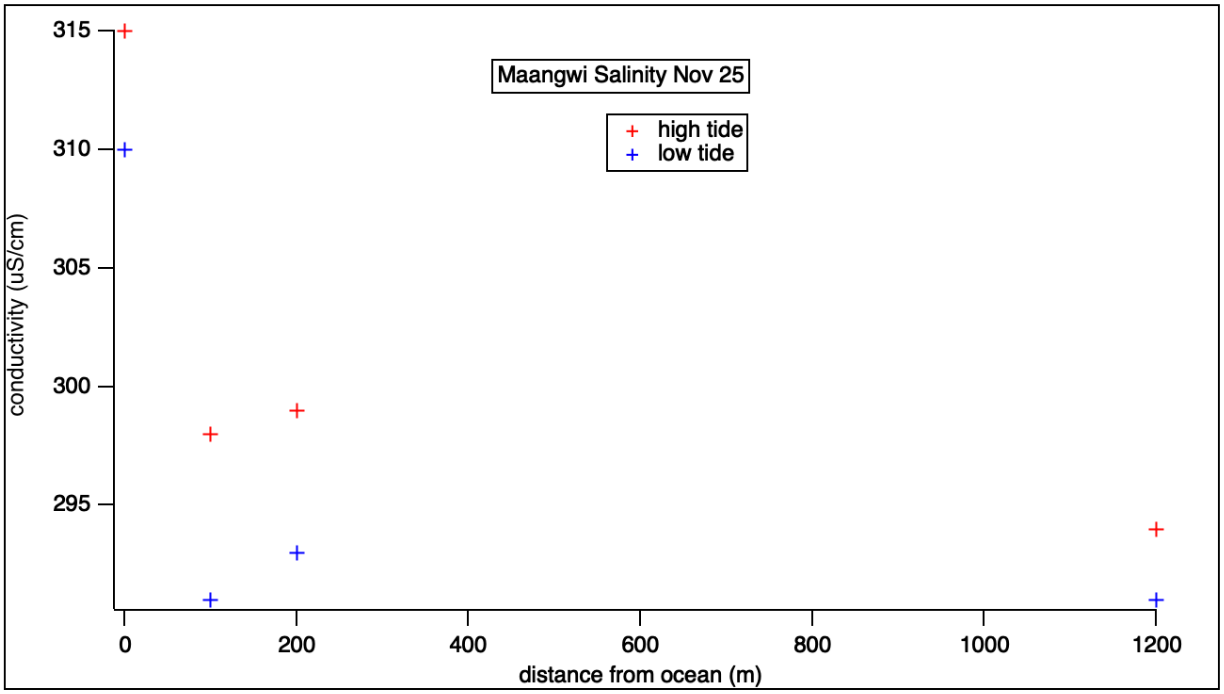

Figure 18: Maangwi Salinity Nov 25. Conductivity values on Maangwi Stream were obtained from water samples collected at intervals from the mangroves to the bridge at the intersection of the stream and the road.

<u>Discussion</u>

The salinity of various coastal Pemba streams was monitored near agricultural areas in order to determine the extent of coastal stream salinity in these regions. Eastern streams were determined to be a greater threat to surface water salinization than western streams, and western stream salinity variation was dominated by precipitation patterns. Geological characteristics, land use, anthropogenic modifications, and precipitation events are dominating forces on stream discharge. Stream discharge counteracts tidal forces in coastal streams where mixing occurs, therefore driving mixing patterns, stratification, and the extent of tidal impact on coastal streams. As land use changes, anthropogenic modification becomes enhanced, and climatic precipitation patterns shift over the long term, stream discharge will also likely be influenced and therefore the extent of surface water salinization.

The stream impacted to the greatest extent was Chamanangwe Stream in eastern Pemba. Chamanangwe showed intrusion further inland compared to any of the other streams through both conductivity measurements and observations. In Figure 14, Chamanangwe shows conductivity values above the 3000 μS/cm mark, which the FAO has determined to be unsuitable for agriculture, as far as 600 m from the start of the mangroves. There was also observational evidence of seawater intrusion such as abandoned farms, dead vegetation, and flooding around the stream at high tide.

In contrast, the other eastern Pemba stream, Maangwi, had conductivity values well below the 3000 μS/cm mark even at the start of the mangroves, as seen in Figure 18. At Maangwi, there is a history of problems involving seawater intrusion and the community has implemented mitigation techniques in response to this, such as physical barriers and planting mangroves. Physical barriers, such as the ridge in Figure 16, protect seawater from moving up the stream and into the rice farms. The mangroves act as protection from storm surges and threats that originate from exposure to the deep sea.

Mitigation strategies implemented by communities in eastern Pemba such as physical barriers and planting mangroves are successful in preventing seawater intrusion into the nearby farms, at least presently. In Figure 18, Maangwi salinity values are well below the agricultural limits, despite the farms' proximity to mangroves and the history of saltwater intrusion in this area. The implementation of mitigation strategies like these may be beneficial to other farms in eastern Pemba, such as Chamanangwe, and western Pemba farms if seawater intrusion is determined to be a greater threat during other times of the year.

Eastern Pemba is more heavily impacted by saltwater intrusion than western Pemba, as seen in the comparison among these sample streams. Eastern Pemba has a much flatter topography than in the west and this greatly amplifies the impact of tides on stream salinity. The greater slope of land in the west helps to protect the tides from pushing seawater as far upstream as in the east. Eastern Pemba is also more exposed to winds and storm surges from the deep sea of the Western Indian Ocean. This exposure leads to an influx of saltwater on the eastern side of the island when compared to the west. The primary form of protection against these storm surges is the mangrove forests in eastern Pemba, but many of these forests are threatened by anthropogenic removal. Many salt farms have been established in eastern Pemba which removes mangrove habitat due to the increased salt concentrations present in these farms. The removal of mangroves reduces coastal protection against storm surges, tidal forces, and therefore surface water inundation of saltwater. Planting mangroves may serve as a beneficial mitigation strategy as seen at Maangwi Stream (Figure 17).

Within western streams, there are a variety of factors that influence the extent of saltwater intrusion. The dominant factor that influences the upstream movement of saltwater is stream discharge, which is closely related to weather and anthropogenic modifications to stream flow. Weni Stream and Mangwena stream are both impacted by anthropogenic modifications to stream flow because they both are dammed. These dams provide upstream rice farms with sufficient water for their crops and therefore reduces downstream discharge from what it would be otherwise. Weni Stream also has a borehole upstream of the sample site that is used for domestic use, further reducing stream discharge from its natural state. In Figures 4-6 and 8-9, there are few to no samples above the 3000 μS/cm limit for suitable agricultural use in either Mangwena or Weni stream past the mangroves. Based on this data, neither stream is immediately threatened by saltwater intrusion, despite evidence of mangrove crabs along the Mangwena Stream banks and local farmer observations of saltwater as far as 800 m upstream on Weni.

Even if saltwater does not regularly intrude this far upstream in either of these sample locations, infrequent intrusion can have long term effects on soil chemistry if salt deposits still remain. The long term effects of saltwater greatly influence vegetative communities, ecological interactions and water quality. Salinity gradients and freshwater/saltwater mixing dynamics greatly influence ecological communities and their biodiversity. As a result, these salinity gradients and salt deposits also influence water and soil viability by local communities due to agricultural water quality restrictions.

Mangwena Stream salinity values varied greatly depending on the amount of rainfall received each day. In Figure 7, there is a correlation between higher rainfall and lower short-term salinity. This relationship is closely tied to stream discharge because an increase in stream runoff increases stream volume, therefore producing greater stream discharge which works as a force opposite to the intruding tidal forces.

The relationship between rainfall and salinity has interesting implications for long term climatic changes on Pemba. If there are noticeable short-term changes to stream salinity following precipitation events, it is likely that there would also be long term changes in stream salinity associated with climatic changes in yearly precipitation patterns based on the idea that these short-term changes would increase in frequency. Rainfall in Zanzibar is currently declining by the rate of 0.01 mm/yr (Kombo, 2019). Less frequent rainfall, as well as overall less rainfall would both contribute to this pattern of increased salinity of coastal streams.

Although the salinity values in Figure 7 are still well below the salinity limits for suitable agricultural use, this pattern of increased salinity is also amplified by other effects brought on by climate change. Sea level rise, as well as an increased frequency of extreme weather events (such as storm surges) are known effects of climate change and both have direct relationships to coastal stream salinity. In areas such as eastern Pemba which are especially vulnerable to storm surges, there are long term effects of these brief increases in salinity, even after any saltwater may have drained back to the ocean. When saltwater reaches farther up the stream than normal, such as during a storm surge, drought, or other extreme weather event, salts are deposited in the soil and this buildup can be detrimental to vegetation. These variables may produce additive effects that could increase the salinity of these streams above the agricultural limits during drier times of the year or in the future.

Local acknowledgement of increased stream salinity largely stems from interactions with the environment over long periods of time and a reliance on the natural systems. This close interaction makes indigenous populations more likely to observe climatic impacts on physical, biological, and seasonal changes. There is also a lack of balance, geographically, of scientific data about climate change, with marine and tropical environments being especially underrepresented (Reyes-Garcia et al., 2015). The importance of comparing the data presented to observations made by western Pemba farmers is not to be overlooked due to the overlap between local and scientific indicators of climate change. The observations provided by these farmers are valuable in contextualizing this issue on a long term scale due to the time continuity provided by their interactions with the environment.

The impacts of climate change on the entire Zanzibar Archipelago and throughout East Africa may produce similar responses on coastal stream salinity regionally . Many other low lying regions in East Africa are also susceptible to saltwater intrusion and increased surface water salinity as a result of changing climatic trends. It is predicted that with climate change, rainfall in this region will become more intense when it does occur (UNDP, 2018). This shift may cause brief decreases in salinity associated with precipitation events, but overall less frequent rainfall will result in surges of increased surface water salinity that may leave behind deposits further upstream than before these climatic changes. The impacts of climate change on African development are extremely widespread. Climate change directly affects these communities and their reliance on their resources for subsidence. Changes in water quality as well as the seasonality and quantity of precipitation can negatively impact coastal agricultural communities throughout the entire region.

Regional adaptation to the impacts of climate change, in this case specifically surface water salinity and saltwater intrusion, is essential to local development. In the face of climate change, sustainable development is only possible when considering the effects of climate change on local economies and how these effects may be mitigated. The mitigation strategies presented at Maangwi Stream serve as an excellent example of community driven mitigation of climate change effects. Farmers have also experimented with farming more saltwater resistant crops. Crops such as coconut, cloves, sugar cane and some species of rice are more tolerable to salt. In many cases, farmers around Pemba have adapted to saltwater intrusion by selecting rice species more suitable to higher salinity. Techniques such as these are useful in preventing, at least temporarily, the effects of saltwater intrusion into coastal farms and are extremely important to food security and development in theses regions. The UNDP report on Climate Change Adaptation in Africa stresses the importance of climate resilience in particularly vulnerable communities that, "depend heavily on climate sensitive natural resources and traditional agricultural practices for subsistence and livelihoods" (2018, p.5).

Conclusion

Until now, there has been a lack of research on salinity in coastal streams on Pemba, the Zanzibar Archipelago, and East Africa. These streams are important to their communities for their use in agricultural and domestic use, but small-scale Pemba farms near the coast are greatly threatened by the inundation of saltwater. Especially in eastern Pemba where the topography is significantly flatter than in the west, saltwater intrusion of surface water is already a large threat. Community mitigation strategies have been successful in reducing the impacts of saltwater intrusion in coastal streams, at least at present. Use of physical barriers to prevent saltwater intrusion and maintaining mangrove forests to protect against storm surges are both good strategies in mitigating the threat of saltwater intrusion.

Compounded with changing climatic patterns in precipitation, sea level rise, and increased extreme weather events, it is expected that these coastal agricultural areas will become more threatened in the future. These coastal agricultural areas are essential to local food security and regional development. Implementing development practices in these regions that consider climatic resilience is essential for the future of this region. An increase in scientific research in this region is also essential to continue monitoring how climate change may amplify the extent of local saltwater intrusion. Natural resources are particularly important to coastal communities on Pemba Island, the Zanzibar Archipelago, and East Africa, further emphasizing the gravity of this issue and its implications on human communities.

Recommendations

This data provides a baseline for stream salinity in Pemba during an especially wet time of year. In the future, inclusion of velocity, streamflow and water stage measurements may be useful to further determine the stratification and mixing dynamics for each stream. Due to the density differences between saltwater and freshwater, it is possible that these streams may be partially or fully stratified, causing saltwater to intrude the bottom of the water column, but not the top where these samples were collected. Stream stage measurements over the course of a tidal cycle would also be useful in visualizing the daily fluctuations of water depth due to tidal influence and the impacts of the changing water levels on the ecological communities. It would also be beneficial to repeat this study during the dry season, because it may show a greater threat of saltwater intrusion on Pemba streams due to a decrease in stream discharge. This study should be repeated in other seasons and in future years to assess how climate change and rising sea levels may be affecting trends in surface water stream salinity. Data collected during the dry season may more accurately match observations made by local farmers and would more accurately portray the extent of year round salt deposits. Coupling this study with interviews of local farmers affected by saltwater intrusion would also help to a gain greater time continuity on this issue.

The outcomes of this study are useful to the Zanzibar government due to the implications that coastal stream salinity has on the livelihoods of local communities. This information may be useful in determining locations on Pemba that are not currently threatened by surface water salinity but may become threatened in the near future. Throughout the Zanzibar Archipelago and East Africa, local governments and farmers may use this information to determine how they may manage and prevent the negative effects of coastal salinization. The mitigation strategies presented here, as well as the dominant factors that influence salinization risk levels provide useful information in determining how coastal communities may adapt and respond to vulnerabilities as a result of climate change.

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